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ABSTRACT

This paper determined the perforation thresholds of laminated, stitched, and two- and three-dimensionally woven composite plates subjected to transverse impact. All composite plates were made from glass/epoxy prepreg tape so direct comparisons could be made about the effects of through thickness reinforcement on perforation threshold. The effects of fiber angle were also studied. The laminated plates were made with stacking unidirectional plies together and had no additional through thickness reinforcement. The stitched plates were reinforced through the thickness with one-millimeter wide strips of prepreg. The two- and three-dimensional plates were hand woven using 12.7 mm wide strips of prepreg. The three-dimensional weaving technique was innovative in that it incorporated new fabric geometry to reinforce the plates through the thickness. A drop weight tester with an instrumented tup was used to impact the plates. The impact test resuts were used to determine the perforation thresholds. The three-dimensional woven plates had larger perforation threshold than the laminated and two-dimensional plates as well as reduced delamination area. The stitched plates had the largest perforation threshold. Through thickness reinforcement increased perforation threshold. The fiber angles of laminated and three-dimensional plates also influenced their perforation thresholds.

INTRODUCTION

Composite materials offer high strength-to-weight and stiffness-to-weight ratios making them excellent candidates for use in structures where strength must be maximized while minimizing weight such as high performance cars and racing boats. Composites can also be used as armor for civilian and vehicle applications due to their high energy absorption capabilities. Their role is to provide penetration resistance, impact energy dissipation, and damage containment [1].

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Material selection of fibers and matrix, stacking sequence, and translaminar reinforcing techniques are some of the factors taken into account when designing composite armor.

Composite materials offer many benefits when compared to conventional metals. Composites can behave very poorly when subjected to transverse loading. One of the worst behaviors of composites is their tendency to delaminate when loaded transversely. Delamination can cause severe reductions in in-plane strength and stiffness, which can lead to failure of an entire structure. This drawback may be one of the biggest limiting factors on composite materials being used in more areas [2]. Other forms of damage are matrix cracking, fiber-matrix debonding, fiber microbuckling, fiber shear-out, and fiber fracture [3, 4].

Composite materials need to be more resistant to transverse loading. The amount of energy that composites can resist before penetration and perforation is reduced by delamination [5]. The motivation of this work was to increase penetration and perforation resistance by reducing delamination. There are two primary ways to achieve this goal; one is to use through thickness stitching and the other is to use woven fabrics.

Laminated composite plates made from unidirectional fibers are susceptible to low velocity impact loads. Transverse damage resistance is especially poor since laminated composites have no through-thickness reinforcement. There have been many studies on laminated composites subjected to low velocity impact as evidenced by the review of Richardson and Wisheart [6]. Most studies agree that the most detrimental damage in composite laminates subjected to impact loading is delamination [2,7]. This type of damage can occur by relatively light impacts while the surface appears to be undamaged [8]. Laminated panels are still attractive because there are no crimp angles to reduce the in-plane properties and fiber volume fractions.

Many methods have been investigated with the goal of increasing the interlaminar fracture toughness of laminated composites. These include using toughened thermosetting matrices, translaminar reinforcement in the form of stitching, z-pinning, knitting, braiding, weaving, and modifying interfacial properties. Some studies have shown stitching can increase compression after impact strengths by 50% and increase Mode I fracture toughness by a factor of 30 [9]. Larsson found that stitching could increase impact delamination energy by more than 20 times when compared to unstitched plates [10]. This is because the stitching improves the delamination resistance energy by raising the Mode I interlaminar fracture resistance of the laminate, which makes it more difficult for a delamination crack to propagate between the fiber plies [11].

Stitching clearly has many benefits, including improved impact damage tolerance and improved delamination resistance to ballistic impact. However, there are problems associated with stitched composites. These include difficulties in stitching complex shapes along with size and thickness restraints imposed by the sewing machines. Large purpose-built sewing machines require extremely high capital costs that are usually beyond the budget of most composite fabricators [12].

Stitching can also decrease in-plane stiffness and tensile and compressive properties by varying amounts [13]. The thread and needle used for stitching can damage the microstructure by breaking, spreading, and crimping the fibers around

the stitch holes. Resin rich regions form around the stitch holes causing possible stress concentration zones [11].

Composite plates made from laminated two-dimensional (2D) woven fabric have received much attention. 2D fabric consists of plain, satin, twill, etc. weaving geometries. 2D fabrics offer improved impact resistance and damage tolerance because of their integrated nature and balanced in-plane properties [14]. Woven fabric laminates have been shown to have Mode I interlaminar fracture toughness of four to five times greater than laminates made of unidirectional fabric. This can be attributed to the roughness of the fabric, resin rich regions between the plies, and the ways in which crack propagation occurs [2]. The resin rich areas tend to arrest the interply cracks and cause them to “jump” between undulations rather than extend continuously. The cracks also have difficulty in propagating because of the undulating paths that occur in the fabric [15]. Woven fabrics also have smaller damage areas after impact, thus they have higher residual compression strength when compared to unidirectional laminates. These strengths can be attributed to the more ductile and compliant nature of woven fabrics [2]. Siow and Shim studied plain weave carbon epoxy plates with a laminate sequence of $[0/90/\text{-}45/45/0/90]_S$. They found the damage mechanisms for woven laminates to be mainly delamination and fiber breakage which were similar to unidirectional laminates [16].

Three-dimensional (3D) composites have become very popular based on their greater delamination resistance, ballistic damage resistance, and impact damage tolerance. Weaving, braiding, stitching, and knitting are all methods for producing 3D composites. The impact energy needed to initiate damage in 3D woven carbon-bismaleimide composites is up to 60% higher than in a laminated counterpart of the same materials. Their Mode I interlaminar fracture toughness values can be 6-20 times higher than unidirectional composites. This group of composites gets their superior properties from the through-thickness binder yarns which can arrest or slow the growth of delamination cracks [12].

Many of the in-plane properties of 3D composites are usually inferior to laminated counterparts when an equivalent amount of fibers are aligned in the load direction. Stiffness values are similar to 2D fabrics but their tension and compression strengths may be lower by 15-20%. The strength reduction is due to the crimping and distortion of in-plane fibers by the binder yarns [12].

This study attempted to determine the energy required to cause penetration and perforation of glass/epoxy composite plates subjected to low velocity impact. The use of only one material allowed direct correlations to be made between fabric geometry and penetration and perforation resistance.

Laminated, stitched, 2D woven, and 3D woven geometries were tested. The laminated geometry was used to produce a baseline for comparing the other geometries to. The laminated plates had no through-thickness reinforcement. The stitched plates were reinforced through the thickness by thread. Each piece of glass/epoxy that made up the 2D woven plate was reinforced, but the pieces were only joined by matrix material. The 3D woven geometry used the fibers, as well a matrix, to join all of the plies together through the thickness.

FABRICATION OF 3D WOVEN PLATES

The three-dimensional (3D) woven plates used a novel manufacturing technique to create a geometry in which 12.7 mm wide strips of prepreg were interwoven in the warp, fill, and through thickness directions as shown in Figure 1.

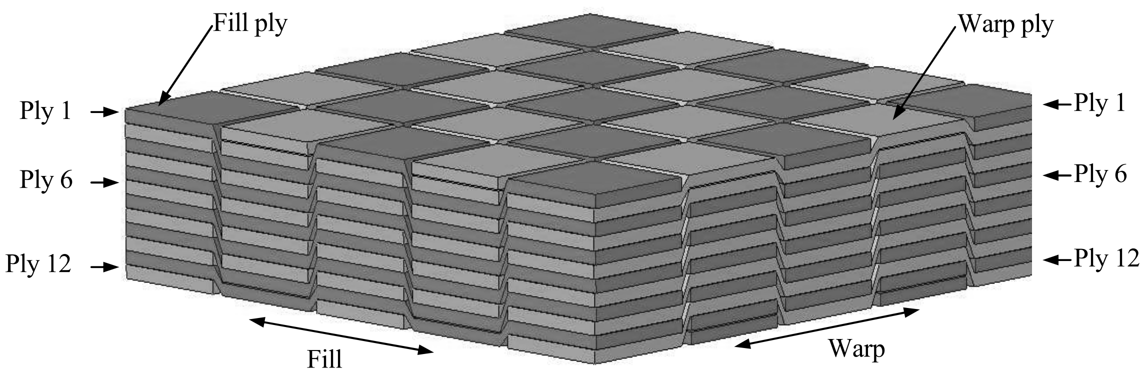
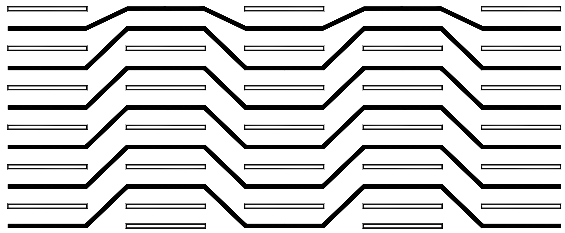
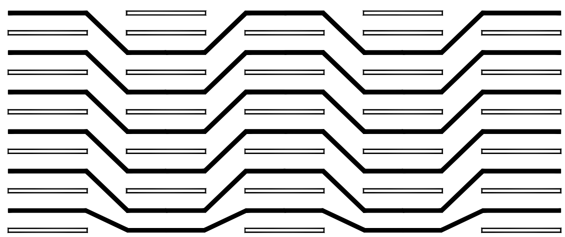


Figure 1. Geometry of three-dimensional woven fabrics.

The geometry was similar to the 2D woven plate; however, each ply of the 3D plate was interwoven with the others. The 2D plate consisted of six pieces of plain-woven prepreg that were joined by the epoxy matrix between them. Figure 1 shows that in the 2D plate plies 1 and 2, 3 and 4, 5 and 6, 7 and 8, 9 and 10, and 11 and 12 were woven together. The 3D plate differs because in the warp direction plies 1 and 2, 2 and 4, 4 and 6, 6 and 8, 8 and 10, and 10 and 12 were interwoven together as shown if Figures 2-7 and 2-8a. Plies 1 and 3, 3 and 5, 5 and 7, 7 and 9, 9 and 11, and 11 and 12 were interwoven in the fill direction as shown in Figures 2-7 and 2-8b. This 3D geometry created a plate with the same thickness as the 2D plate but without having only the epoxy matrix to connect each layer.



(a) warp direction



(b) fill direction

Figure 2. Three-dimensional weave geometry in warp and fill directions.

The procedure for creating the 3D woven plate was extremely time consuming and labor intensive. This geometry required that each fill row be completed before the next could begin. No automation was incorporated into weaving the plates as no equipment could be found that could create the 3D geometry, thus all weaving was done by hand. All warp strips of the first ply had to be taped, paper backing side up, to a warp board only at one end before weaving could begin. A section of the paper backing was removed from the end of each strip where the tape was placed. The next ply of strips then had to be placed directly over the previous ply, paper backing removed, and taped to the warp board. This procedure was repeated until all strips of six plies were taped to the warp board. The other ends of the strips were not taped as in the two-dimensional weaving. The fabricated plates consisted of twenty-six strips per ply with the panel having six plies in the warp direction and six plies in the fill direction.

The warp board and strips were secured to an elevated work surface with the paper backing down. Non-perforated Teflon fabric was used to prevent the strips from sticking to the work surface. The 3D weaving process required that warp strips and associated paper backing be folded back in the sequence presented in Figure 2. The paper backing remained on the warp strips until they were folded back. The length of paper backing removed depended on the fill angle, but enough length had to be removed so that none remained between the warp strips and fill strips during the weaving of each row. Figure 3 shows step 3 prior to placing a fill strip over the warp strips for the 3D[($\underline{0/90}$)$_6$] plate. The fill strips are folded back and the paper backing has been trimmed.

3D woven plates had orthogonal as well as non-orthogonal angles between warp and fill strips. The fill strips were placed at angles of 15, 30, 45, and 90 degrees from the warp strip direction. These plates were designated as 3D[$(\underline{0/15})_6$], 3D[$(\underline{0/30})_6$], 3D[$(\underline{0/45})_6$], and 3D[$(\underline{0/90})_6$]. The plates had dimensions of 300 mm x 300 mm after the edges were trimmed. An optical microscope image of the cross section of a portion of a 3D[$(\underline{0/90})_6$] specimen at a magnification of 120X is shown in Appendix A.

The procedure for weaving the next fill row followed the same steps. However, the warp strips that were folded back and then placed over the fill strips would change. For example, in step one, the warp strips in rows 1, 3, and 5 would be folded back and all but one strip in rows 2 and 4 would be folded back. The completed second fill row should look like that given in Step 8 of Figure 2-9. The remaining odd fill rows should be the same as the first fill row while the remaining even fill rows will be the same as the second fill row.

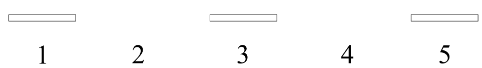
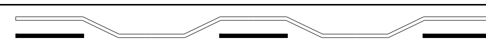
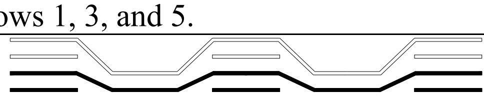
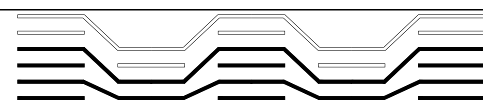
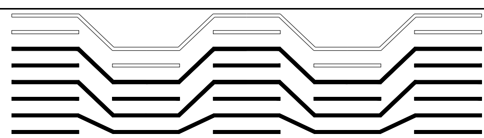
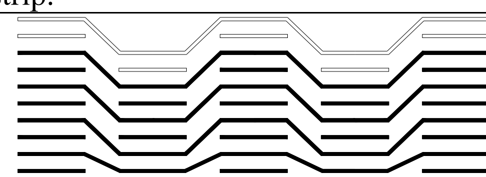
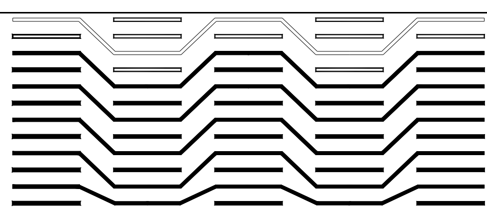
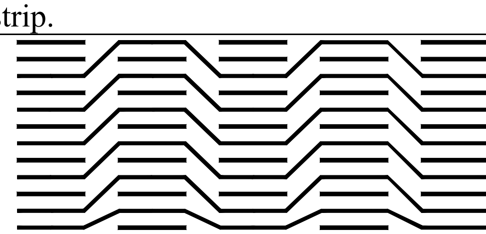
 Step 1. Fold back all warp strips in rows 2 and 4. Fold back all but one strip in rows 1, 3, and 5.	 Step 2. Place a fill strip over warp strips 1, 3, and 5.
 Step 3. Place another warp strip over the first fill strip in rows 1, 3, and 5. Place another fill strip over the warp strips.	 Step 4. Place warps strips in every row over the last fill strip. Add another fill strip.
 Step 5. Place warp strips in every row over the last fill strip. Add another fill strip.	 Step 6. Place warp strips in every row over the last fill strip. Add another fill strip.
 Step 7. Place warp strips in every row over the last fill strip. Add the final fill strip. Then place two warp strips in rows 2 and 4 to complete the row.	 Step 8. Repeat steps 1-7 for the second fill row and each successive fill row until all 26 fill rows are completed. Steps 1-7 only show 5 out of 26 warp rows.

Figure 3. Weaving procedures for 3D woven plate.

EXPERIMENTAL RESULTS

Low-velocity impact tests were performed for identifying The specimens tested have had varying degrees of through-thickness reinforcement. The laminated specimens had no through-thickness reinforcement. The only material joining the plies was the thin layer of matrix between them. There were no fibers contributing to any through-thickness strength.

The stitched specimens and laminated specimens were similar in that they were both initially L[$(0/90)_6$] specimens. The stitched specimen used 1 mm wide strips of prepreg as stitching thread to join the plies together. Stitching through the thickness with a 12.5 mm x 12.5 mm square pattern proved to be the best through-thickness reinforcement method, among the composites tested, as shown in Figure

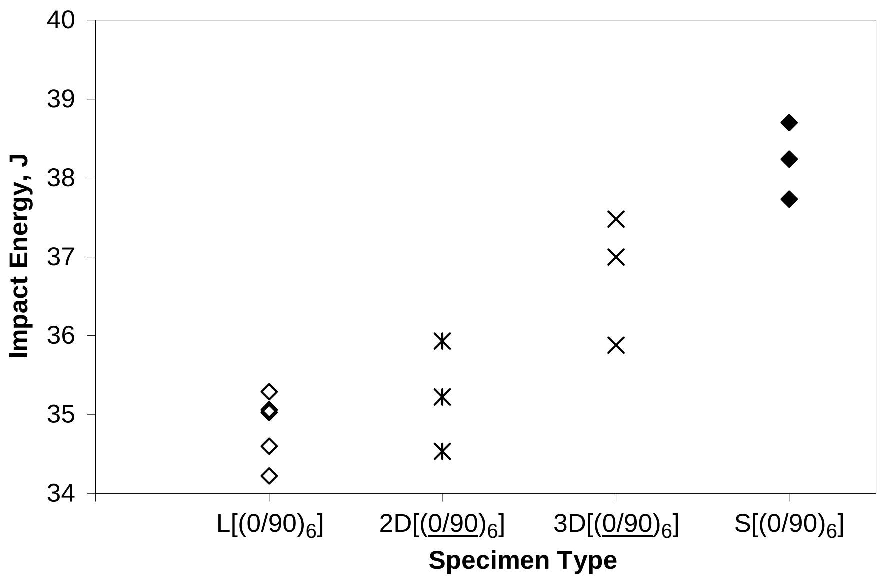


Figure 4. Impact energy interval of [$(0/90)_6$] specimens.

4. It was likely that this stitching pattern was an efficient selection. A stitching pattern with large dimensions may not have been efficient enough. On the other hand, a stitching pattern with smaller dimensions may have caused higher stress concentrations.

Each piece of the two-dimensional woven specimens consisted of two plies that were interwoven. This interweaving reinforced each piece. Six pieces were then stacked together to form the completed two-dimensional woven specimens. As a result, the two-dimensional woven specimens had more through-thickness reinforcement than the laminated specimens. This caused the two-dimensional woven specimens to require slightly more energy to begin penetration and perforation than the laminated specimens. Thus, the two-dimensional woven specimens had higher perforation thresholds than the laminated specimens.

The three-dimensional woven specimens were reinforced through the thickness by fibers although they were not oriented in the thickness direction. This made them more resistant to perforation when compared to the two-dimensional woven and laminated specimens.

The 3D woven plates were fabricated with four different θ values that were 15°, 30°, 45°, and 90°. Four of the laminated plates shared the same θ values. The results from the testing of these specimens are shown in Figure 5. The solid symbols represent the 3D woven specimens. The L[$(0/7.5)_6$] results are shown for comparison. The 3D woven specimens had larger energy intervals than the laminated specimens. This was the most obvious when looking at the results of the 3D[$(\underline{0/15})_6$] specimens. The 3D[$(\underline{0/30})_6$] specimens performed slightly better than L[$(0/30)_6$] specimens. The testing results showed less impact energy was required to begin perforation in the 3D[$(\underline{0/45})_6$] specimens when compared to the L[$(0/45)_6$] specimens. The energy interval for the 3D[$(\underline{0/45})_6$] specimens was larger while the energy to cause perforation was greater. The 3D[$(\underline{0/90})_6$] specimens showed the largest improvement on perforation resistance when compared to the L[$(0/90)_6$] specimens with the same θ value. The 3D woven specimens increased penetration resistance by nearly 1.7 J. Perforation resistance was increased by over 2 J. Visual inspection showed a decrease in delamination area, which seemed to not propagate as far from the impacted area as in the other specimens. The undulations in the 3D woven fabric seem to retard the delamination growth.

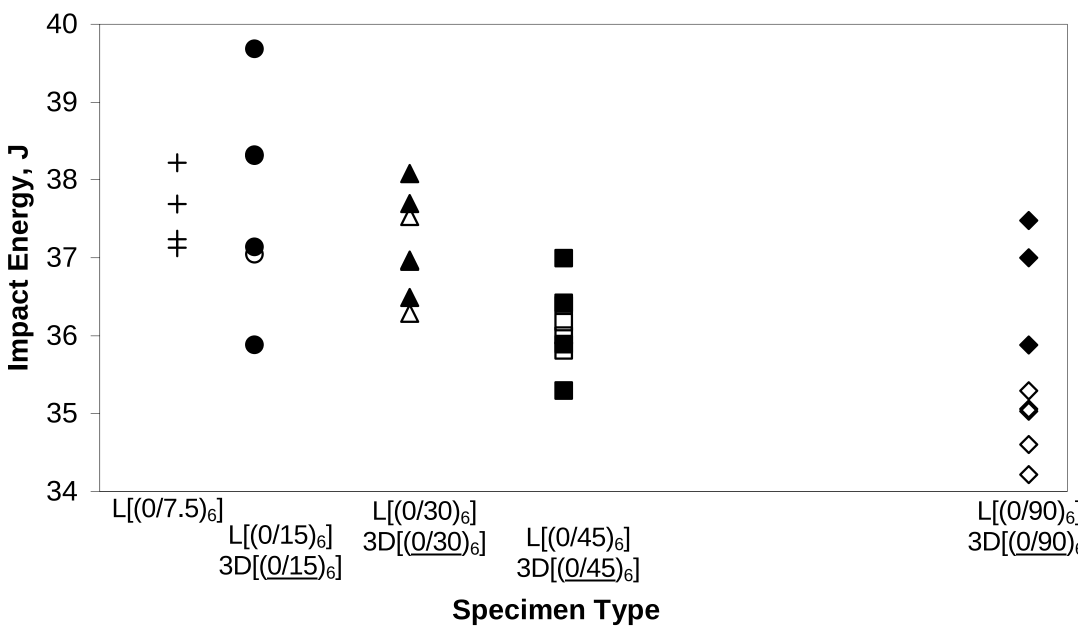


Figure 5. Impact energy interval of specimens with equal θ.

Figure 6 compares L[$(0/45)_6$] specimen 5 to 3D[$(\underline{0/45})_6$] specimen 6. They were subjected to impact energies of 36.39 J and 36.42 J, respectively. Delamination is shown by the darker areas of the specimens when the specimens are placed on a light table and photographed. The laminated specimen delaminated more than the 3D woven specimen. The delamination of the bottom ply extends almost the entire length of the specimen. The 3D woven specimen delamination seemed to be constrained to the center of the specimen; it passed slightly beyond the undulations of the warp and fill strips.

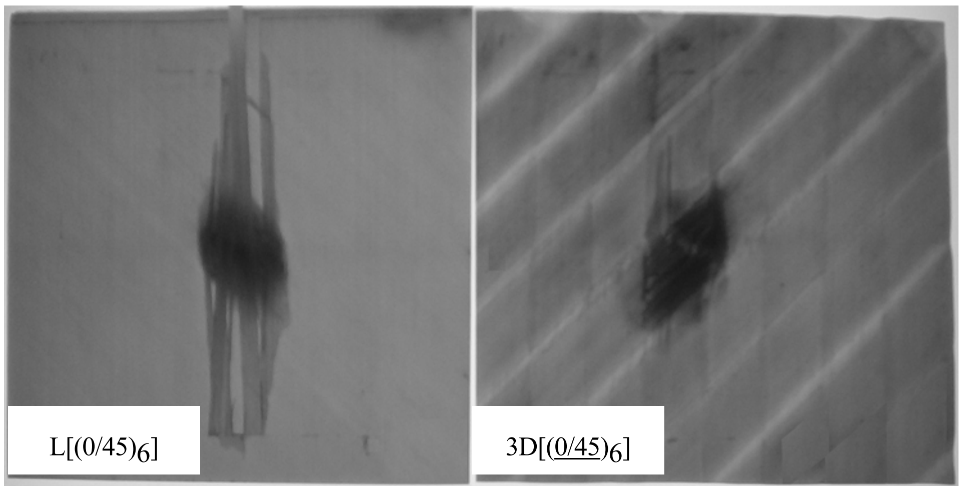


Figure 6. Delamination of L[$(0/45)_6$] and 3D[$(0/45)_6$] specimens.

The delamination of 2D[$(\underline{0/90})_6$] specimen 1 and 3D[$(\underline{0/90})_6$] specimen 1 is compared in Figure 7. The specimens were impacted with energies of 34.53 J and 34.57 J, respectively. The delamination area of the 2D specimen was larger than the 3D specimen. The 2D specimen had delamination extend away from the impact point. The 3D specimen seems to contain the delamination to an area close to the point of impact, i.e. at the center of the unit cell.

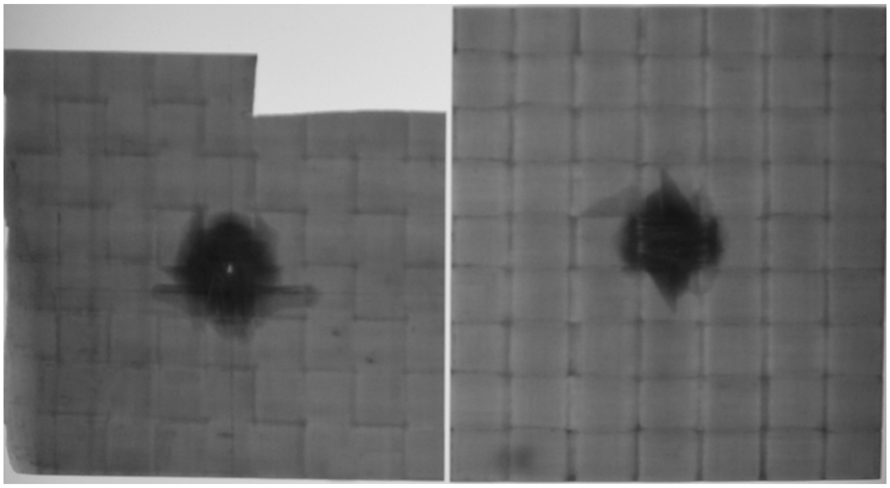


Figure 7. Delamination of 2D[$(\underline{0/90})_6$] and 3D[$(\underline{0/90})_6$] specimens.

SUMMARY

Composite plates made from glass/epoxy were laminated, stitched, and woven with two-dimensional and three-dimensional fabric geometries. Laminated specimens constructed with θ angles of 7.5° and 15° had higher penetration and perforation resistance than specimens with θ angles of 30°, 45° and 90°. These results supported the hypothesis that small fiber angle values can increase penetration and perforation resistance. The stitched specimens had the largest penetration and perforation thresholds. The three-dimensional woven specimens outperformed the laminated and two-dimensional woven specimens. The 3D[$(\underline{0/15})_6$] and 3D[$(\underline{0/30})_6$] had larger penetration and perforation thresholds than the other three-dimensional specimens, which supports the fiber angle effect. The three-dimensional woven geometry was shown to have good impact resistance most likely due to the innovative way of linking each ply together.

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